for Silicon Optoelectronics

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Abstract— **The basic optoelectronic properties of self-forming InGaAs/InAlAs QDs are examined in parallel with their device implementation. Recent results showing remarkably good tolerance to radiation induced point defects and good luminescence emission from InAs/InGaAs QDs grown on dislocation arrays are discussed in terms of an enabling technology which will allow optoelectronics integration with silicon technology.**

Index Terms—**Nanotechnology, Stranski-Krastanow quantum dots, photoluminescence, III-V compounds.**

I. Introduction

Semiconductor Quantum Dot (QD) lasers with low threshold currents and high gain [1, 2], and QD Infrared Photodetectors [3] capable of incident photon absorption are already showing successful technological implementations of the unique optical properties of self-forming Semiconductor Quantum Dots (QDs). Future device applications include the use of coupled QDs as the basic structures in the fabrication of cellular automata in novel computing architectures [4] and frequency domain optical storage devices [5] based on self-assembled QDs.

The basic properties of quantum dots and the most recent implementations of QD based devices are described here. Recent result showing superior radiation hardness compared to 1-D devices (QWs) are also related to their strong optical emission near misfit dislocations arrays. These properties make III-V QD based optoelectronics ideally suited for integration with Si-based systems, since dislocations are unavoidable in GaAs/Si heteroepitaxy, and thus QDs could fill the gap for optoelectronic components in system on a chip (SoC) applications.

II. Background on Structural and Optical Properties of Self-Forming Semiconductor Quantum Dots

Until recently, true, defect free, quantum box confinement in semiconductor structures existed only in theoretical treatments. The so called Self-assembled or Stranski-Krastanow quantum dots have provided opportunities to test theoretical predictions with the eventual achievement of defect free 3-D confined semiconductor quantum dots compatible with thin film technology.

Low luminescence intensities observed in ex-situ fabricated QDs became more prevalent as dimensions were reduced so that surface effects dominate. Attempts to manufacture quantum dots made use of photolithography and etching. While providing good control of positional order and offering design flexibility; processing affects interfaces, introducing impurities and surface damage that limits the optical performance of these quantum structures.

The realization that taking advantage of monolayer control in molecular beam epitaxy (MBE) and metallorganic chemical vapor deposition (MOCVD) growth systems can be used to form strained nanometer sized InAs or InGaAs islands of remarkable uniformity, originated an entire sub-field, and is an important contribution to present day nanotechnology. Semiconductor quantum dots can be fabricated by taking advantage of a strain induced transformation that happens naturally in the initial stages of growth for lattice mismatched materials that have the same crystal structure. The growth starts layer by layer, and after a certain strain defined critical thickness is reached, the structure spontaneously

before the islands reach a size for which strain relaxation and misfit dislocations occur. This spontaneous island formation during growth precludes the interface quality problems often associated with ex-situ processed quantum structures of low dimensionality.

The optical properties of self-forming or self-assembled QDs include ultra-narrow line-widths [9] and large inhomogeneous broadening. Zero-dimensionality results in the sharp density of states that explain ultra-narrow inhomogeneous line widths, which are temperature independent (do not broaden with kT) from 4 to 70 K [10, 11]. Inhomogeneously broadened PL from ensembles has been explained as a contribution from structural differences with dot sizes and compositions [12]. Ensemble strain interactions were later identified to also contribute to this broadening from the QD neighboring strain interactions, which do not depend on individual dot size differences or compositions variations [13].

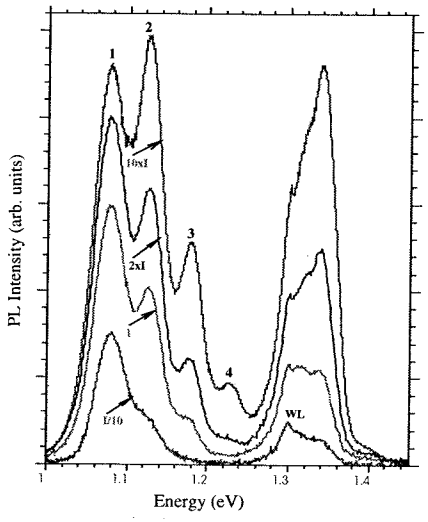

Figure 1. PL spectra taken at different excitation powers from InGaAs/GaAs QDs. The spectra shows wetting layer (WL) luminescence and emission from excited states. The unit excitation power density I ≈ 5 W/cm^2. Energy levels are labeled 1, 2, 3 and 4 for the ground state, first, second and third excited states respectively. Relative intensities between WL luminescence and luminescence from QD

spectra. As seen in Figure 1, peaks from QD states show more prominently at higher energies as the excitation intensity is increased. Figure 1 shows the PL spectra from InGaAs/GaAs QDs as a function of optical excitation power. Excited state emission can be observed even at very low excitation power, with emission from the (i+1) levels before the (ith) level saturates. The sample producing the spectra shown here contains a concentration of 4 x 10^8/cm^2 InGaAs QD with 25 nm average diameters. A small spread in island sizes gives small inhomogeneous broadening, which allows resolving excited states. The spectra seen in figure 1 thus reflects the excited states emission of a single quantum dot. Calculations based on lens shaped QDs [15] predict 4 bound states for these dot dimensions. These results are then in reasonable agreement with calculations.

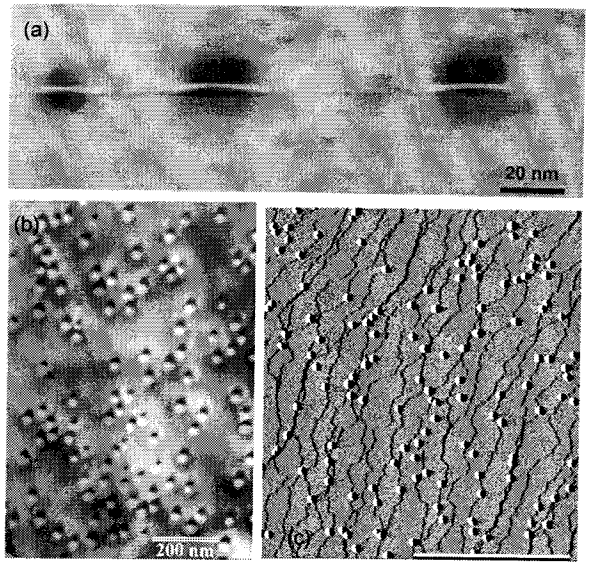

Figure 2. (a) Cross sectional transmission electron microscopy (TEM) image (dark field) from InAs/AlGaAs quantum dots, showing strain contrast in the barrier material. (b) Plan view TEM micrograph (2 beam condition) of InGaAs/GaAs QDs showing the characteristic dark/bright lobes. (c) Force microscopy image (deflection image) of surface InGaAs QDs on a surface oriented 0.5 degrees from the exact (100) orientation. Lines are mono and bi-atomic steps, which act as preferential nucleation sites for QDs.

which are strongly material dependent and to some extent, controllable by adjusting growth temperatures, group V partial pressures, and other factors to be further discussed in section IV. In general, self-forming quantum dots have a shallow aspect ratio, and can be approximated by a disk or a lenticular shape [9]. Fig. 2 shows some typical strain contrast images from Transmission Electron micrographs in both cross section and plan view from InAs and InGaAs QDs, as well as surface image taken by surface probe microscopy, that shows both QDs and surface steps which accommodate slight deviations from the perfect (100) orientation.

Most of the optical properties of InGaAs QDs can be conveniently observed in structures with varying dot densities, which can be obtained with positionally varying growth rates [16]. The evolution of Stranski-Krastanow (S-K) quantum dot (QD) formation in a ternary ($In_{0.6}Ga_{0.4}As/GaAs$) was studied with graded structures grown via organometallic vapor phase epitaxy. Surface probe microscopy showed island evolution between 3.5 and 6.5 monolayers (ML) deposition. Island densities were seen to increase exponentially (over three decades with 0.2 ML deposition) before saturation ~ 4.7 ML. Photoluminescence (PL) of similar capped structures showed that the wetting layer (WL) PL energy did not shift beyond the onset of the S-K transition. From figure 3 it can be seen that the evolution of the luminescence spectra from these structures can be divided into 4 distinct regions, shown in groups from bottom to top in figure 3: WL emission, simultaneous WL and QD emission, QD saturation, and last, the dislocation/coalescence regime. Luminescence emission begins with a thin QW which progressively red shifts (becomes thicker) as InGaAs deposition is increased. This is indicated in the lower portion of figure 3. In the next stage, the QD concentration rises until the threshold for QD PL detection. Once the QD PL peak increases in intensity, the WL peak diminishes

deposition, the PL QD emission does not change significantly. This stage corresponds to island saturation. In the last stage, the PL intensity drops in magnitude to roughly a third of its former intensity, and stays at this lower intensity over the next ~ 2 ML deposition. It can be seen from the spectra in figure 3 that PL emission intensities from QDs increases as their concentration increases, and that the WL emission is reduced. However, the energy of the weaker WL PL peak stays at the same value once the QD PL peak becomes detectable and grows. This indicates that the WL thickness does not increase (or decrease) with further InGaAs deposition once the QD start forming.

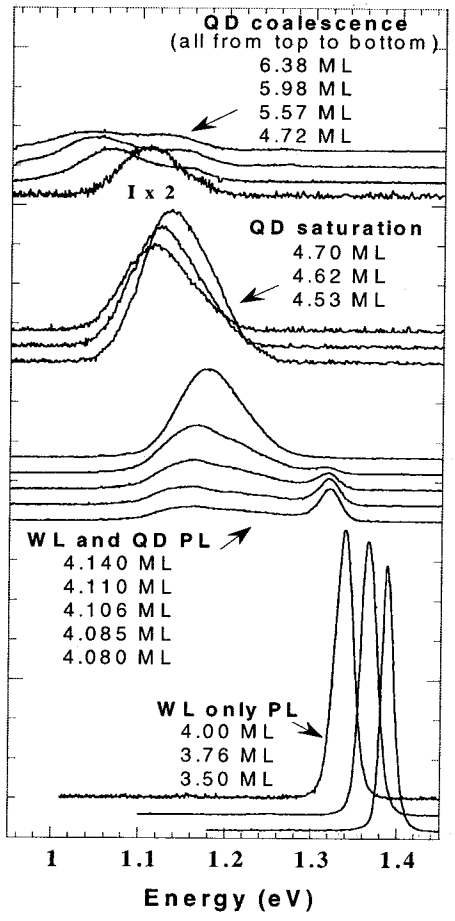

Figure 3. PL spectra and calibrated relative intensities in different regimes of QD formation. Shown in separate groups from bottom to top: WL PL shifts before QD formation, evolution of PL spectra at low QD densities when both QD and WL peaks are simultaneously observed,

intensities observed after reaching saturation island densities was attributed to island coalescence and incoherent island formation. The excitation power dependence of the luminescence at different stages of QD evolution also showed a concentration dependence of optical saturation in self-forming InGaAs QDs, which was later confirmed in further studies [13].

I. QDs Optoelectronic devices

A. *Frequency domain optical storage*

The most distinctive optical properties of QD ensembles are ultra-narrow homogeneous line-widths, temperature independent line-width, and large inhomogeneous broadening. These features make self assembled QDs specially attractive for higher temperature persistent spectral hole-burning (PSHB) applications, as proposed by Muto [5]. In QD structures used in laser applications, full widths at half maxima (FWHM) of 80 meV and even 100 meV are reported for their PL spectra. This has the consequence that only a small portion of the QDs in the material will contribute to lasing, and it offsets some of the advantages of the much larger gain obtained from individual quantum dots. In standard laser diode applications, a common aim is to achieve good size uniformity in these quantum dot structures.

This naturally occurring broad emission and absorption in QDs is exploited in optical storage applications based on PSHB for which QWs are not suitable. For frequency domain optical storage (FDOS) applications, obtaining a very broad optical absorption is very desirable. QD ensemble PL broadening can be as large as 200 meV for some QD materials systems [17], and while reducing this value is difficult, increasing it can be achieved by stacking QD layers with slightly different dot sizes and/or compositions. Line-widths can be as narrow as .09 meV [10,11] making multiplexing ratios of 2000 already achievable. The single major advantages of using

10^{11}/cm^2 have already been achieved [18], and stacking of quantum dot arrays has also been demonstrated, this means that densities of 10^{12}-10^{13}dots/cm^2, with storage densities of 10^{10} bits/cm^2 are ultimately possible. QD memories would also offer the possibility of room temperature operation and good design flexibility: the emission and absorption can be tuned, the depth and shape of the confining potential can be adjusted, and inhomogeneous broadening can be increased. Most importantly, semiconductor QDs can be integrated with semiconductor thin film technology in monolithic structures with either Silicon or III-V substrates.

B. *Zero-dimensional lasers*

QD based lasers were first proposed by Arakawa and Sakaki [19], due to the greater gain and lower tresholds currents that are expected with reduced dimensionality, as well as the expected temperature independence of their threshold current. Large gain can be expected from the greater oscillator strength resulting from 3-dimensional confinement. This has been verified when comparing QDs and similar QWs in recent studies [18], which show that similar integrated luminescence intensities can be achieved with much smaller volumes of InAs or InGaAs QDs, than from QWs from the same materials.

Since the first reported implementations of QD InAs and InGaAs lasers [20, 21], threshold currents as low as 5.2 Amps/cm^2 have been demonstrated [22] for InAs QD lasers operating at 200 K. The threshold currents at room temperature are still not as low as what has been achieved in similar QW lasers, however, saturation material gains for QD lasers are as high as 150,000 cm-1 (as compared to 3,000 cm-1 for QW lasers) and QD lasers maximum differential gains are orders of magnitude higher than what is reported for QW laser diodes. The recent commercialization of QD lasers for wavelengths division multiplexing (WDM) applications show a rather unique application of QD lasers, since it

C. *QUANTUM DOT INFRARED PHOTODETECTORS (QDIPs)*

Unlike Quantum Well Infrared Photodetectors (QWIPs), QDs are sensitive to normal incident infrared light, which enhances the quantum efficiency and reduce fabrication complexity and eventually cost. Most of all, QD infrared photodetectors (QDIPs) are expected to exhibit lower dark current due to weaker electron-phonon coupling. Because of their in-situ formation during III-V heteroepitaxy, QDs can be easily integrated with mature processing technologies, similar to processing developed for QWIPs. These have the potential for fabricating large format detector arrays and monolithic integration. Furthermore, the QDIPs have a broader infrared response range due to the several discrete states in QDs. Recent results demonstrate broad-band normal-incidence detection with a responsivity of a few hundred mA/W at detection wavelengths of ~ 5 microns [24].

IV. TUNING QUANTUM DOT EMISSION ENERGIES.

Issues of interest in this rapidly growing field of self-assembled nanostructures include the ability to tune island dimensions and their surface densities. This in turn means control of their luminescence wavelengths for certain technologically desirable target emissions. Tunability in zero-dimensional semiconductor technology thus offers obvious advantages in extending the range of possibilities for devices. Some of the approaches to achieve different sizes and concentrations are: variations with temperature, different group V partial pressure and by increases in substrate miscut angle. Thermally activated group III adatom mobilities result in larger diameters and lower concentrations with increasing deposition temperatures. These variations are have been shown for InGaAs/GaAs and AlInAs/AlGaAs, where striking differences are seen [18]. Tunability in the InGaAs/GaAs QD concentration can also be obtained in MOCVD by varying the arsine flow and in MBE by changing the Arsenic

examples of how these techniques applied to InGaAs QDs produce dramatic differences in either sizes or concentrations.

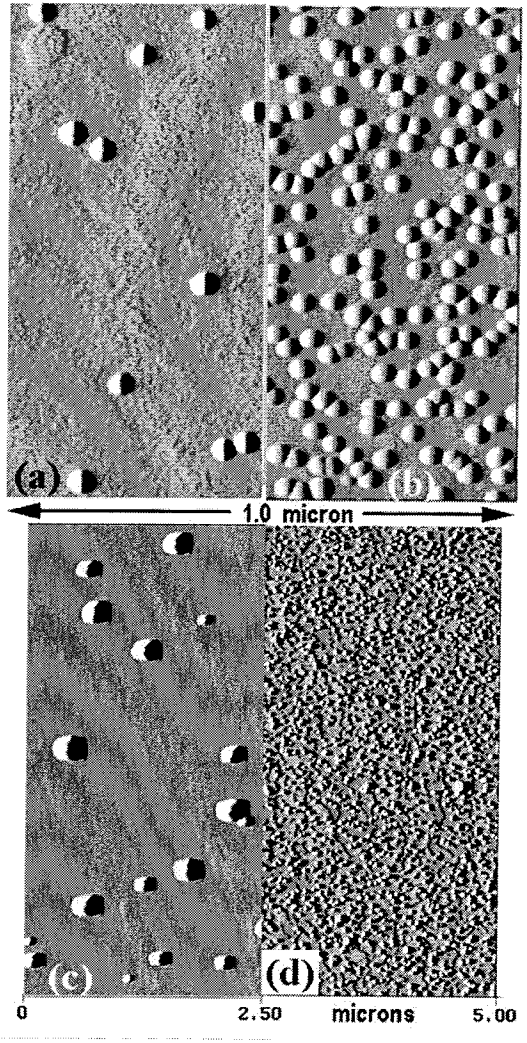

Figure 4. Ranges in Sizes and uniformities that can be obtained in III-V QD growth. Results are shown here for InGaAs QDs, where (a) shows that similar sizes but widely different concentrations can be obtained by changing the group V partial pressure, and (b) shows variations obtained by changes in growth temperature.

Substrate orientation is also be a key factor in island nucleation: Changes in vicinal orientation near (100) can be used to exploit the preferential step edge nucleation at mono and multi-atomic steps [25], so varying miscut angle can be used to change island densities and sizes. Anisotropies in

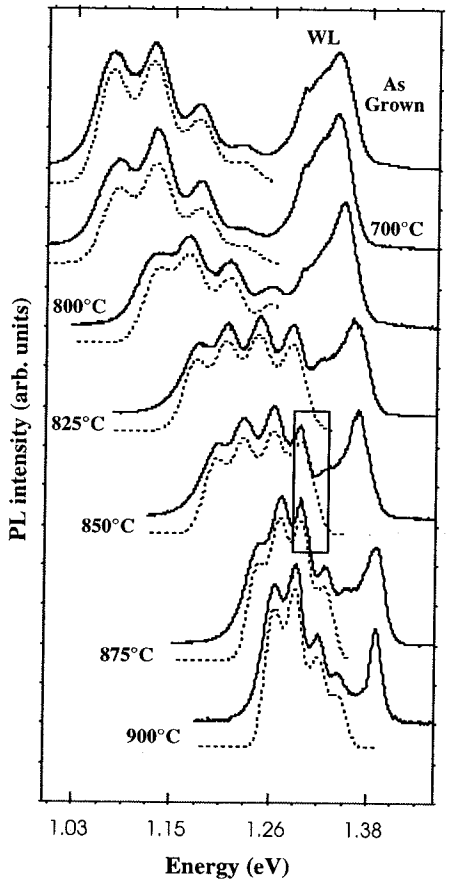

Figure 5. Effects of compositional intermixing of the InGaAs/GaAs interface on the radiative emission of QDs that show excited states luminescence. Dashed lines show the results of simulation by solution of the rate equations.

Tuning QD emission wavelengths by thermally induced compositional disordering of the dot/barrier interface is a straightforward method to achieve blue-shifts in InGaAs/GaAs, InGaAs/AlGaAs and InAlAs/AlGaAs quantum dots. Recent studies found that greater blue-shifts can be obtained in QDs than in QWs for the same value of diffusion lengths, furthermore, inhomogeneously broadened PL peaks narrow significantly with dot/barrier interdiffusion [26]. Fig. 5 also shows that the intersublevel spacings from excited states emission in QDs can also be tuned. The effects of interdiffusion on excited state emission from QDs demonstrates that

transitions.

V. QDs NEAR NON-RADIATIVE CENTERS: DISLOCATION ARRAYS AND POINT DEFECTS

Some of the fundamental properties of QDs suggest that optoelectronic devices incorporating QDs could tolerate greater radiation damage than other heterostructures, and that their radiative efficiencies would remain high in the midst of other types of nonradiative defects, like dislocations. One of them is based on a simple geometrical argument: the total volume percentage of the active QD region is very small. Specifically, in self-forming InGaAs/GaAs QDs surface coverage range from 5% to 25%, depending on growth conditions. Therefore, the chance of finding radiation-induced defects in the active region is reduced. Also, exciton localization in the quantum dots due to three-dimensional confinement will also reduce the probability of carrier non-radiative recombination at radiation induced defect centers.

Minimizing the impact of radiation-induced degradation in optoelectronic devices is important for several applications. In space, protons pose a particularly severe threat to both planetary and Earth-orbiting spacecraft because they produce damage effects by several mechanisms. Because of their mass, protons can cause significant displacement damage in the semiconductor lattice, which is the primary cause of severe performance degradation and failure in several types of semiconductor devices. The effects of proton irradiation are also of interest in the use of ion beam modification or "defect engineering" in electronic materials, since proton implantation is often used for device isolation in compound semiconductors.

Figure 6 shows some results from a comparative study where QDs and QWs of similar composition and capping layer thicknesses were simultaneously irradiated with 1.5 MeV protons [28].

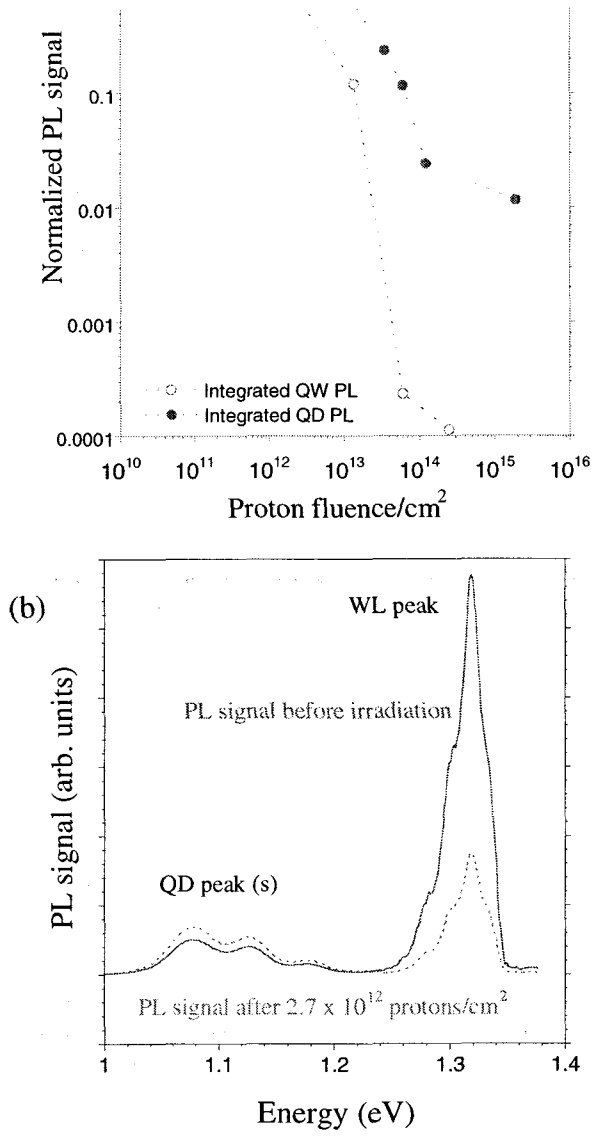

Figure 6. (a) Integrated PL emission normalized to the as-grown samples for QW and QDs as a function of proton dose, and (b) comparison of initial and post irradiation (proton dose 2.7 x 10^{12}/ cm^2) spectra of low density InGaAs/GaAs QDs (3.5 x 10^8 dots per cm^2). The spectra, obtained at constant excitation, show simultaneous emission form QD and wetting layer states.

Recent results that report measurements of the radiation resistance from QD lasers to both 8 MeV Phosphorus ions [29] and to energetic protons [30] show orders of magnitude greater radiation tolerance from QD lasers than from QW lasers of the same types of materials.

deposition of optically active QDs on Silicon [31]. This is confirmed by the observation of very bright PL emission even after formation of a dislocation array [32] and the fabrication of functional InAs lasers on Silicon [33]. These observations have important consequences. They demonstrate the promise of QD devices in harsh radiation environments, due to localized optical processes in QDs, where 3-D confinement prevents wave-function overlap with defect centers, thus protecting QD structures from potential damage from radiation effects or dislocation related damage.

Epitaxial Growth of InAs/GaAs on Si substrates has shown good PL yield with only a slight shift in the emission energy [31]. The implementation of III-V QD devices on Silicon will require examination of the effects of damage in the barrier (and wetting layer) since electron hole pairs are typically formed in the barrier and wetting layer and then recombine from QD states. A lower optical emission from QD states can thus reflect poor carrier diffusion lengths in the barrier material rather than damage directly in the QDs. Dislocation climb and glide could affect structural features in QD based devices outside of the active areas and also affect device performance. Therefore, dislocation motion into active device areas should be investigated and device stability established for long term applications of III-V QDs on Silicon substrates.

VI. SUMMARY AND CONCLUSIONS

In summary, it was shown that the unique optical properties of QDs are already giving promising results in devices applications, and furthermore, these same properties that result in higher gain in lasers and in incident photon absorption in detectors (QDIPs) can make QD devices impervious to non-radiative centers. These centers originate from radiation induced defects or from misfit dislocations formed by strain relaxation from growth on materials with dissimilar lattice constants. Such findings are

VII. ACKNOWLEDGEMENTS:
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REFERENCES:

1. D. L. Huffaker and D. G. Deppe, 'Electroluminescence efficiency of 1.3 μm wavelength InGaAs/GaAs quantum dots' *Appl. Phys. Lett.* 73, 520 (1998).
2. A. V. Uskov, K. Nishi, and R. Lang, 'Collisional broadening and shift of spectral lines in quantum dot lasers', *Appl. Phys. Lett.* 74, 3081 (1999).
3. J. Phillips, K. Kamath, and P. Bhattacharya, 'Far infrared conductivity from InAs quantum dots', *Appl. Phys. Lett.* **72**, 2020 (1998).
4. A. O. Orlov, I. Amlani, G. Toth, C. S. Lent, G. H. Bernstein, G. L. Snyder, "Experimental demonstration of wire using quantum cellular automata", *Appl. Phys. Lett.* **74**, 2875 (1999).
5. S. Muto, "On A Possibility Of Wavelength-Domain-Multiplication Memory Using Quantum Boxes", *Jpn. J. Appl. Phys.* **34**, L210-212 Feb. (1995).
6. Leonard D, Krishnamurthy M, Reaves CM, Denbaars SP, Petroff PM, "Direct Formation Of Quantum-Sized Dots From Uniform Coherent Islands Of InGaAs On GaAs-Surfaces", Appl Phys Lett vol. 63, pp 3203-3205, Dec.1993.
7. Moison JM, Houzay F, Barthe F, LePrince L, Andre E, Vatel O, "Self-organized growth of regular nanometer-scale InAs dots on GaAs", Appl. Phys. Lett. 64, 196 (1994).
8. Notzel R, Temmyo J, Tamamura T, "Self-Organized Growth Of Strained InGaAs Quantum Disks", Nature 369, 131 (1994)
9. R. Leon, P. M. Petroff, D. Leonard, and S. Fafard, "Spatially-Resolved Visible Luminescence of Self-Assembled Quantum Dots", *Science* **267**, 1966 (1995).
10. R. Leon, P. M. Petroff, D. Leonard, and S. Fafard, "Temperature effects on the radiative recombination in self-assembled quantum dots", *Surf. Sci.* **361-362**, 778 (1996).
11. Raymond, S.; Fafard, S.; Charbonneau, S.; Leon, R.; Leonard, D.; Petroff, P.M.; Merz, J.L., "Photocarrier recombination in AlInAs/AlGaAs self-assembled quantum dots", *Phys. Rev. B* **52**, 17238 (1995)
12. R. Leon, S. Fafard, D. Leonard, J. L. Merz, and P. M. Petroff, "Visible luminescence from quantum dots in large ensembles", *Appl. Phys. Lett.*, **67**, 521 (1995).
13. Leon R, Marcinkevicius S, Liao XZ, Zou J, Cockayne DJH, Fafard S, "Ensemble interactions in strained semiconductor quantum dots", Phys. Rev. B vol. 60, R8517-R8520, Sep. 1999.
14. S. Fafard, R. Leon, D. Leonard, J.L. Merz, and P. M. Petroff, "Phonons and radiative recombination in self-assembled quantum dots", *Phys. Rev. B* **52**, 5752 (1995).
15. A. Wojs, P. Hawrylak, S. Fafard and L. Jacak, "Electronic Structure and Magneto-optics of self-assembled quantum dots" Phys. Rev. B 54, 5604 (1996).
16. R. Leon and S. Fafard, "Structural and radiative evolution in quantum dots near the InxGa1-xAs/GaAs Stranski-Krastanow transformation", *Phys. Rev. B* **58**, R1726 (1998).
17. R. Leon, C. Lobo, T. P. Chin, J. M. Woodall, S. Fafard, S. Ruvimov, Z. Liliental-Weber, and M. Stevens-Kalceff, "Self-forming InAs/GaP quantum dots by direct island growth", *Appl. Phys. Lett.* **72**, 1356 march (1998).
18. R. Leon, C. Lobo, A. Clark, R. Bozek, A. Wysmolek, A. Kurpierski, and M. Kaminska, "Different paths to tunability in III-V quantum dots", *J. Appl. Phys* **84**, *pp* 248 July (1998).
19. Y. Arakawa and H. Sakaki, "Multidimensional quantum well laser and temperature dependence of its threshold current", Appl. Phys. Lett. Vol 40, pp 939

properties of Heterostructures with InGaAs quantum Clusters", Semiconductors vol 28, pp. 832 Aug (1994).
21. J. Temmyo, E. Kuramochi, M. Sugo, T. Nishiya, R. Notzel, and T. Tamamura, "Strained InGaAs quantum disk laser with nanoscale active-region fabricated with self-organization on GaAs (311)b substrate", Electron. Lett. Vol 31, pp. 209-211, Feb (1995).
22. G. Park, O. B. Shchekin, D. L. Huffaker, and D. G. Deppe, "InGaAs quantum dot lasers with sub-milliamp thresholds and ultra-low threshold current densities below room temperature", Electron. Lett. Vol 36, pp 1283-1284, Jul 2000.
23. H. Jones-Bey, "Quantum-dot lasers enter telecom fray for Wavelength-Division Mulitiplexing", Laser Focus World, Volume 36, issue 11, November 2000.
24. Liu HC, Gao M, McCaffrey J, Wasilewski ZR, Fafard S, "Quantum dot infrared photodetectors", *Appl. Phys. Lett.* Vol. 78, pp 79-81 Jan. 2001.
25. R. Leon, T. J. Senden, Yong Kim, C. Jagadish and A. Clark, "Nucleation transitions for InGaAs islands on vicinal (100) GaAs", *Phys. Rev. Lett* **78**, 4942 (1997).
26. R. Leon, D. R. M. Williams, J. Krueger, E. R. Weber and M. R. Melloch, "Diffusivity transients and radiative recombination in intermixed $In_{0.5}Ga_{0.5}As$/GaAs quantum structures", *Phys. Rev. B* **56**, R4336 (1997).
27. R. Leon, S. Fafard, P.G. Piva, S. Ruvimov and Z. Liliental-Weber, "Tunable Intersublevel Transitions in self-forming Semiconductor Quantum Dots", *Phys. Rev. B* **58**, R4262, (1998).
28. R. Leon, G. M. Swift, B. Magness, W. A. Taylor, Y. S. Tang, K. L. Wang, P. Dowd, and Y. H. Zhang, "Changes in Luminescence Emission Induced by Proton Irradiation: InGaAs/GaAs degradation resistance of quantum dot lasers to radiation damage", Appl. Phys. Lett., vol 77: (5) 624-626 JUL 31 2000
30. Ribbat C, Sellin R, Grundmann M, Bimberg D, Sobolev NA, Carmo MC, Enhanced radiation hardness of quantum dot lasers to high energy proton irradiation, Electron. Lett., vol 37: (3) 174-175 FEB 1 2001
31. Gerard JM, Cabrol O, Sermage B, "InAs quantum boxes: Highly efficient radiative traps for light emitting devices on Si", Appl. Phys. Lett., vol 68: (22) 3123-3125 MAY 27 1996
32. Leon R, Okuno JO, Lawton RA, Stevens-Kalceff M, Phillips MR, Zou J, Cockayne DJH, Lobo C, "Dislocation-induced changes in quantum dots: Step alignment and radiative emission", Appl. Phys. Lett., vol. 74: (16) 2301-2303 APR 19 1999.
33. K. K. Linder, J. Phillips, O. Qasaimeh, X. F. Liu, S. Krishna, P. Bhattacharya, and J. C. Jiang, "Self-organized In0.4Ga0.6As quantum-dot lasers grown on Si substrates", Appl. Phys. Lett. Vol. 74, pp 1355-1357, Mar. 1999.